

**Fermi National Accelerator Laboratory**

**FERMILAB-Conf-94/183**

# **Scintillating Fiber Detector Performance, Detector Geometries, Trigger, and Electronics Issues for Scintillating Fiber Tracking**

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**June 1994**

Presented at *Frontier Detectors for Frontier Physics, 6th Pisa Meeting on Advanced Detectors*, La Biodola, Isola d' Eolo, Italy, May 22-28, 1994

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# Scintillating Fiber Detector Performance, Detector Geometries, Trigger, and Electronics Issues for Scintillating Fiber Tracking

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## ABSTRACT

Scintillating Fiber tracking technology has made great advances and has demonstrated great potential for high speed charged particle tracking and triggering. The small detector sizes and fast scintillation fluors available make them very promising for use at high luminosity experiments at today's and tomorrow's colliding and fixed target experiments where high rate capability is essential. This talk will discuss the current state of Scintillating fiber performance and current Visual Light Photon Counter (VLPC) characteristics. The primary topic will be some of the system design and integration issues which should be considered by anyone attempting to design a scintillating fiber tracking system which includes a high speed tracking trigger. Design constraints placed upon the detector system by the electronics and mechanical sub-systems will be discussed. Seemingly simple and unrelated decisions can have far reaching effects on overall system performance. SDC and D0 example system designs will be discussed.

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## 1. Current Fiber and VLPC Performance

During 1992-1994, the Fiber Tracking Group<sup>\*\*\*</sup> has achieved several important milestones in the development of scintillating fiber tracking technology. First, a beam test was executed at Brookhaven National Laboratory to study track resolution and track triggering for a 96 element fiber tracker using SDC-style fibers and wave guides and readout with VLPCs. This work established a minimum tracking resolution of  $\sim 150 \mu\text{m}$  for a double layered fiber ribbon [1], and established a clear tracking and triggering capability of a fiber tracker in stand-alone mode. Second, a comprehensive study of light yield from single-clad and multi-clad scintillating fibers has established a new international standard for the detection of scintillation light over long distances ( $\sim 10 \text{ m}$ ).

The experiment consisted of 3 m long scintillating fibers of  $830 \mu\text{m}$  diameter optically coupled to 8 m long wave guide fibers of  $965 \mu\text{m}$  diameter read out with VLPCs. For the case of multi-clad scintillating fiber and wave guide, an average of 6.2 photoelectrons was detected from the far end of the scintillating fiber if the fiber was unmirrored, and 10.2 photoelectrons if the fiber end was mirrored. With this substantial photoelectron yield, minimum-ionizing tracks can be easily detected in fiber arrays, and

excellent performance characteristics are expected for the fiber trackers designed for the D0 experiment at the Fermilab Tevatron Collider and for other experimental applications.[2].

## **2. General Comments**

### *2.1. System and Sub-system Integration*

A variety of important parameters must be considered when constructing a scintillating fiber tracker to be used as part of a high speed trigger. These parameters effect the physics performance (off-line event reconstruction and track finding algorithms) of the detector, the cost to design, the cost to construct, and trigger performance of the detector as a system.

In order to build a functioning tracking system, all subsystems must be considered before the design is finalized. It is possible to design a system which does a superb job of off-line track reconstruction, but which is incapable of making a fast trigger and may cost an astronomical amount to instrument.

### *2.2. Important Considerations*

It is vital that the system designers consider the following requirements and how they effect the design decisions. These requirements include (but are not limited to):

- 1) **Functionality:** How well does the system provide performance for both off-line reconstruction and for high speed real time triggering.
- 2) **Designability:** Does the proposed solution pose insurmountable problems for any subsystem, electronic or mechanical.
- 3) **Maintainability:** Can the proposed systems be reliably maintained with a minimum effort, this affects access requirements, repair vs. replace, and diagnostics costs.
- and 4) **Affordability:** Can the proposed system be designed and built within reasonable cost constraints? Does any one part of the overall system force any other subsystem into a situation where its only recourse is to be overly expensive or impossible. It is imperative that all parts of the system design be considered as to their effects on the overall system cost and performance.

## **3. Design Strategy**

It is useful to think of the design problem as one existing in a multi-dimensional space, where the dimensions are: off-line track reconstruction performance, trigger performance, power consumption, cost to construct mechanically, cost to construct electronics, cost to maintain system, and delivery schedules. The design team will want to maximize the performance and minimize the cost of the system. We will discuss what design parameters can be varied to achieve some of these goals. SDC and D0 specific designs will also be discussed. Only designs for colliding beam experiments will be discussed, although many of these discussions lend themselves to fixed-target experiments as well.

### 3.1. Electronics Design and Sub-system Support

The design strategy for the electronics has been to provide: 1) high-rate performance to avoid introduction of dead time into the system, and 2) hermetic trigger coverage. It is undesirable to have seams or holes where the trigger efficiency would be low.

### 3.2. Electronics Architecture

Architecturally, the electronics for the Scintillating Fiber Tracker and Trigger has been discussed elsewhere [3][4].

## 4. Trigger Methodology

### 4.1. Superlayer Structure

The basic tracking structure chosen for the scintillating fiber tracker is one in which several superlayers are used. A superlayer is made up of multiple layers of scintillating fibers typically made from several layers of fiber doublets. Each fiber doublet layer is made by joining two single fiber ribbons together. A sample superlayer is shown in Figure 1.

The superlayers are arranged as concentric cylinders at various radii from the interaction point. The choice of these radii affects many of the system performance parameters. Examples of a typical geometry are shown in Figure 2. Each superlayer is comprised of fiber ribbon doublets, some to measure the  $R-\Phi$  coordinate and others to measure U and V coordinates of tracks passing through the superlayers. This superlayer scheme allows for minimum complexity in mechanical design and provides off-line reconstruction of several space points for each track. Each superlayer which participates in the trigger has two separated doublets that measure  $R-\Phi$ .

### 4.2. High $P_T$ Track Triggering

A high speed (level-1) trigger scheme

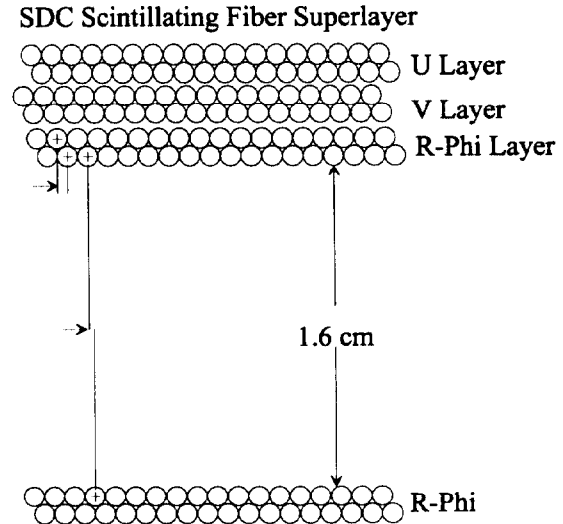


Figure 1. Superlayer structure used for SDC. Each superlayer has 4 doublets 2  $R-\Phi$  and a single U and V.

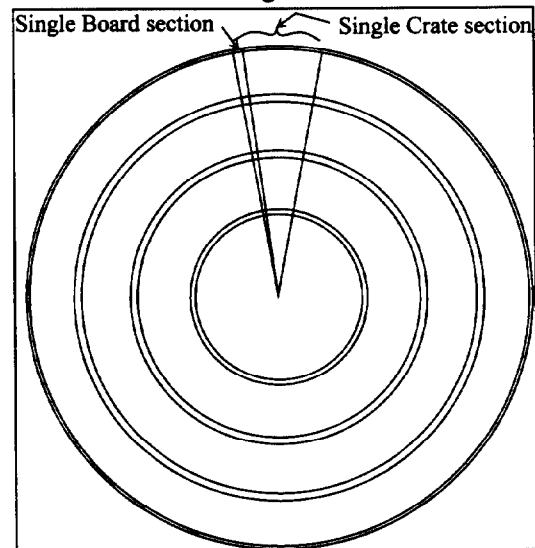


Figure 2. Axial view of scintillating fiber tracker showing superlayers at various radii.

has been developed based on recognizing high  $P_T$  tracks in a scintillating fiber barrel tracker. Only the  $R-\Phi$  coordinate is used in the trigger, since this is the appropriate component to measure the transverse momentum,  $P_T$ , in an axial magnetic field. The reader will see from later discussions that to obtain  $Z$  coordinate trigger information from the stereo layers of fibers,  $U$  and  $V$  layers, is very difficult.

The trigger system is designed to find high  $P_T$  tracks very quickly and report them to a global trigger system for linking with other subsystem trigger information. The basic method used for the trigger is one in which track "segments" or stubs are found within each superlayer. These "segments" are then linked to form tracks. These two processes, segment finding and segment linking, are applied in parallel across the entire detector, so that the delay from the arrival of the hit information from the interaction to the reporting of a found track to the trigger system can be as little as 100 ns.

At the speeds required for a level 1 tracking trigger, there is little or no time for unraveling the placement or positions of the fibers. This information must be "hard wired" into the system from the very beginning. Thus, the design and construction of the tracker must make provisions for the electronics requirements from the start.

#### 4.3. Tracker Segmentation

Figure 2, which shows a typical superlayer structure, also shows how the tracker must be segmented to allow for the formation of a trigger in a very short time span. The tracker is segmented into  $\Phi$  slices, where each slice is identical to all other slices. Each  $\Phi$  slice is handled by a single readout board, which allows for all of the information needed to form a track trigger to be resident on the board. Only a small number of adjacent channel hits need be shared between adjacent  $\Phi$  slices in order to create a "seamless" trigger. Figure 3 shows the  $\Phi$  slice (not to scale) for a single readout board and particle trajectories which cross the inter-board boundary and must have their hits "shared" across this boundary. If, in the design process, this type of symmetry is not included, each  $\Phi$  slice would be different and each readout board would be unique. This would lead to a very expensive system and would be a difficult system to maintain.

#### 4.4. Track Segment Finding.

The algorithm for track segment finding uses a fixed pattern of combinatorial "AND/OR" logic to find

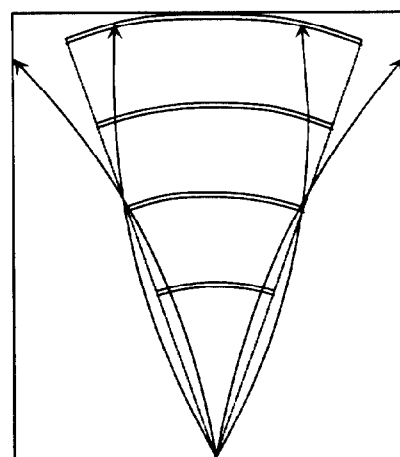


Figure 3.  $R-\Phi$  slice of a 4 superlayer tracker showing charged particle trajectories which cross Board/Crate boundaries

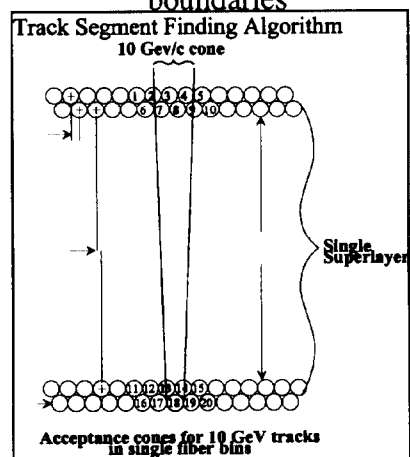


Figure 4. Segment finding.

high  $P_T$  hits in a given quartet layer with a resolution of one fiber diameter. If the correct symmetry is maintained, the segment finding for each single fiber position would require four 4-input AND gates and one 4-input OR gate.[4] Figure 4 shows the two  $R-\Phi$  doublets of a single superlayer. The reader can see that the number of logic terms needed to specify a track-segment which lies within a 10 GeV/c cone is small. In the SDC implementation, each track-segment-finding ASIC has 16-fiber bins to cover so that it requires 64, 4-input AND gates and 16, 4-input OR gates. If one were to allow for fiber inefficiencies and develop logic based on "2-fiber" segments, the number of terms would increase by a factor of 3, but this is still a small number of AND and OR terms. ASICs of this size and complexity are common, and if one does not need the 63 MHz performance that SSCL required, these ASICs could be replaced with Field Programmable Gate Arrays (FPGAs).

The number of fibers which must be shared across ASIC/CARD/CRATE boundaries is 5 in and 5 out per 64 element section. This permits the system to find all track segments without any gaps or dead spots in the trigger coverage. However, if the symmetry described is not maintained, the number of fibers shared across boundaries would grow very large and the number of AND and OR terms in each ASIC would have to grow to accommodate the variations from  $\Phi$  slice to  $\Phi$  slice. The designer is urged to not let this happen, as the cost of the electronics will grow rapidly.

#### 4.5. Track Segment Linking

The task of linking the individual track segments into tracks can be accomplished by a scheme similar to that used for segment finding. Provided that the superlayer design maintains a  $\Phi$  slice symmetry, each linker ASIC has the same task as all other linkers and the number of AND and OR terms needed is small.[5] Thus by using a relatively small amount of combinatorial logic we can examine the entire set of hit positions for tracks which satisfy the stiffness or  $P_T$  requirement. Requiring segments from three superlayers serves to reject false tracks. It is also possible to make a range of  $P_T$  triggers by requiring that the tracks are less inclined than the minimum  $P_T$  track. This allows the system to report a  $P_T$  code including a sign bit and some number of bits of  $P_T$  information, based upon the slope of the track within the

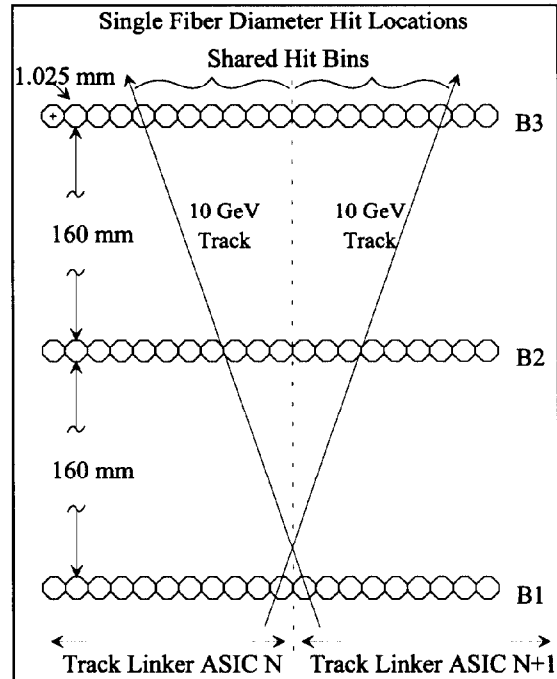


Figure 5. Triplet of superlayers used for SDC Trigger.

trigger layers. Figure 5 shows a typical segment linker  $\Phi$  slice for SDC. Note the minimum  $P_T$  threshold for SDC was 10 GeV/c. The trigger tracks are then reported to the trigger system for linking to the calorimeter and/or muon systems. Because this "processing" is done in parallel across the entire tracker, the time needed to form the trigger can be very short, typically less than 100 ns.

The combinatorial AND-OR logic of the segment linker can be designed to be remotely programmable within certain limits. Hence as luminosity increases or the demands on the trigger change, trigger thresholds can be changed dynamically to increase the effective  $P_T$  threshold. As with the segment finder, the complexity and cost of the segment linker grow rapidly as the symmetry of the tracker is broken.

## 5. Tracking System Geometries

Detector geometries can have a very strong influence on the performance and cost of the tracking system. Once geometries are fixed, many of the parameters of the electronics are constrained. For this reason, these geometries must be investigated as to their impact on other parts of the system before they are frozen. Once frozen, these geometries are "hard wired" into the system. The layer separation and fiber spacing both contribute to this "hard wired" information. They also affect the designability of the electronics systems. Figure 6 shows three possible barrel tracker trigger superlayer configurations. Each of these has different performance capabilities. Each of these will be discussed briefly.

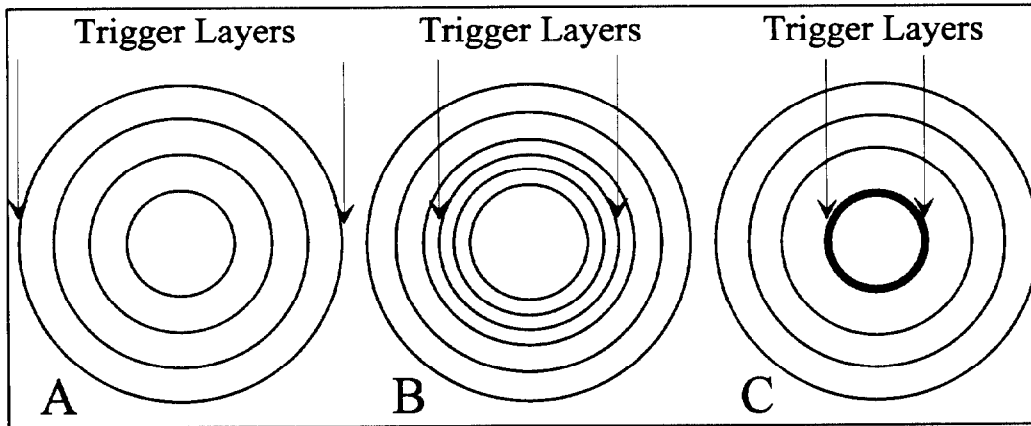


Figure 6. Various options for trigger superlayer in a barrel tracker.

### 5.1. Trigger Requirements

Option A has the greatest span in trigger layer spacing and so has the sharpest trigger threshold and the lowest  $P_T$  trigger capability. This larger trigger lever arm also implies that the number of interconnections which cross  $\Phi$  boundaries is greater. Since more fibers participate in each  $\Phi$  section, this configuration is also more susceptible to



fake tracks. The "search paths" over which the electronics must look for tracks are wider and thus random hits are more likely to satisfy the track conditions for a trigger.

Option C has the smallest trigger lever arm and its trigger threshold would be fairly "soft". However, since the layers are very closely spaced, it has the smallest search paths for the trigger and so the number of fake tracks would be reduced and the number of interconnections is the smallest of the three options.

Option B is a compromise between A and C. This option most closely matches that chosen for SDC. The trigger layers are spaced closely to provide sharp trigger threshold, maximum coverage in  $\eta$ , and an acceptably low fake rate. As the reader can see, there are many parameters which interact to determine the overall system performance.

Option A was chosen for the D0 tracker, to provide a sharp trigger threshold for low  $P_T$  ( $>1.5$  GeV/c) tracks in compact geometry. The number of channels in the D0 trigger is small ( $\sim 36,000$ ) and the tracker itself is small,  $R \leq 50$  cm, so the problem of shared fiber interconnects is manageable.

## 5.2. Electronics requirements

In order to avoid cracks or areas where the trigger is inefficient, all of the layers must communicate correctly with each other. In a system such as that designed for SDC, which has  $\sim 500,000$  active fibers, the system must reside in a reasonable number of circuit boards  $\sim 1000$ . To be affordable and maintainable, there must not be 1000 unique circuit boards, but rather a single species of board duplicated 1000 times into which is incorporated the symmetry of the  $\Phi$ -slice. This requirement implies that a symmetry be created and maintained in the system so that each board provides a region of coverage that is the same for all boards, and that all circuit board boundaries are the same. Since the trigger only uses R- $\Phi$  measurements, it is logical to create and maintain a symmetry in the  $\Phi$  coordinate. Thus, each circuit board will cover a  $\Phi$  slice of the detector as shown in Figure 2.

These requirements provide some constraints on the detector configuration. If each circuit board is to cover a  $\Phi$  slice of the detector, all  $\Phi$  slices must be the same. This implies that superlayer spacing and fiber spacing or diameter must be adjusted to create and maintain an X-fold symmetry, where X is the number of trigger circuit boards in the system. In this way, all trigger boards are the same and a given board's position within the system is not important. This means that any board is interchangeable with any other, and maintenance/replaceability is trivial. If this symmetry cannot be maintained, then each board is unique, and the user is faced with a system which has X different boards and the potential need for X different spare boards. This would create a system which is neither affordable nor maintainable. Thus to implement fiber track triggering for SDC,  $\Phi$ -slice symmetry was designed in from the beginning at the board level to the ASIC level as well.

### 5.3. Connector Issues

Once symmetry is created in the detector as described above, this symmetry must be preserved by the interconnect system used to bring the required signals into each of the trigger boards. This can be accomplished most easily in the clear wave guide fibers which bring the light signals from the scintillating fibers to the VLPC cassettes. If one creates a  $\Phi$  symmetry as shown in Figure 7, where each layer's contribution to the  $\Phi$  section is a multiple of  $N$  fibers, then the task of signal routing is greatly simplified.

It is possible to make fiber interconnects which support greater than  $N$  fibers each for both the fiber ribbons on the detector and for the VLPC cassette interconnections. The only constraint is that the number of fibers in each connector be an integer multiple of  $N$ . This scheme has many advantages in that all of the clear wave guide fiber bundles are the same. This leads to ease in manufacture and makes availability and replacement of spares straight forward.

The proposed D0 solution has 4 superlayers at approximate radii of 20, 30, 40, and 50 cm. By choosing the fiber spacing for the ribbons to be approximately .9 mm, a detector symmetry may be created. By choosing 5 different ribbon spacings of .984 mm, .905mm, .931mm, .943mm and .951mm, a fiber layout is created which has 4 superlayers and which has a 40 fold symmetry in  $\Phi$ . Furthermore, the value for  $N$  is found to be 64, providing for a very manageable connection system in fibers and ribbons. Each trigger cassette has 14 optical connectors with 64 fibers/connector. The total number of optical connectors for the entire trigger system is 560.

The alternative to creating and maintaining this symmetry is a system where  $N=1$  and every fiber of the 36,000 trigger fibers must be placed into the correct VLPC slot by hand. Such a system would be neither affordable nor maintainable.

### 5.4. U and V Stereo Layers

As can be seen from the preceding arguments, certain system designs can lead to rapid growth in the number of interconnects which leads to a system which cannot be built. An example of such a system arises if one tries to make a trigger using the stereo layers. Each U fiber crosses a great many V fibers (even for small stereo angles), and the number of interconnections needed to make a trigger would be larger than the number of fibers. For this reason, the stereo fibers are not used in a fast trigger. Possible methods of getting Z information for the trigger have been discussed elsewhere[4].

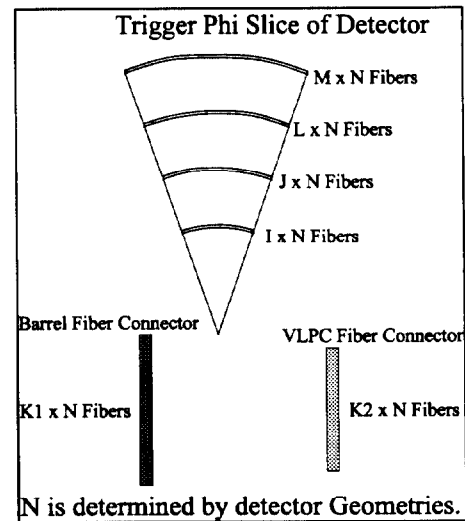


Figure 7.  $\Phi$  symmetry and connector possibilities

## 6. Conclusions

It is hoped that the reader will now have a better understanding as to the ways in which different parameters interact to make or break a working system. All component subsystems within a larger trigger system must cooperate to create an architecture which yields a sensible level 1 trigger.

## 7. Acknowledgments

This work was supported by the U.S. Department of Energy through Fermi National Accelerator Laboratory.

The author wishes to thank the many members of the SDC Scintillating Fiber Tracking Group for their work and understanding.

Special thanks is also given to Andrew Romero and Kelly Knickerbocker from Fermilab for their work and long hours fabricating and running a test beam prototype trigger board.

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